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[54] MONOLITHIC MM-WAVE PHASE SHIFTER USING OPTICALLY ACTIVATED SUPERCONDUCTING SWITCHES

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[51] **Int. Cl.**[5] **H01P 1/18**; H01P 3/08; H01B 12/00

[52] **U.S. Cl.** **505/1**; 505/703; 505/848; 505/866; 333/161; 333/995

[58] **Field of Search** 333/161, 156, 164, 138, 333/103, 104, 995; 505/700-703-856, 862, 860, 866, 848, 849

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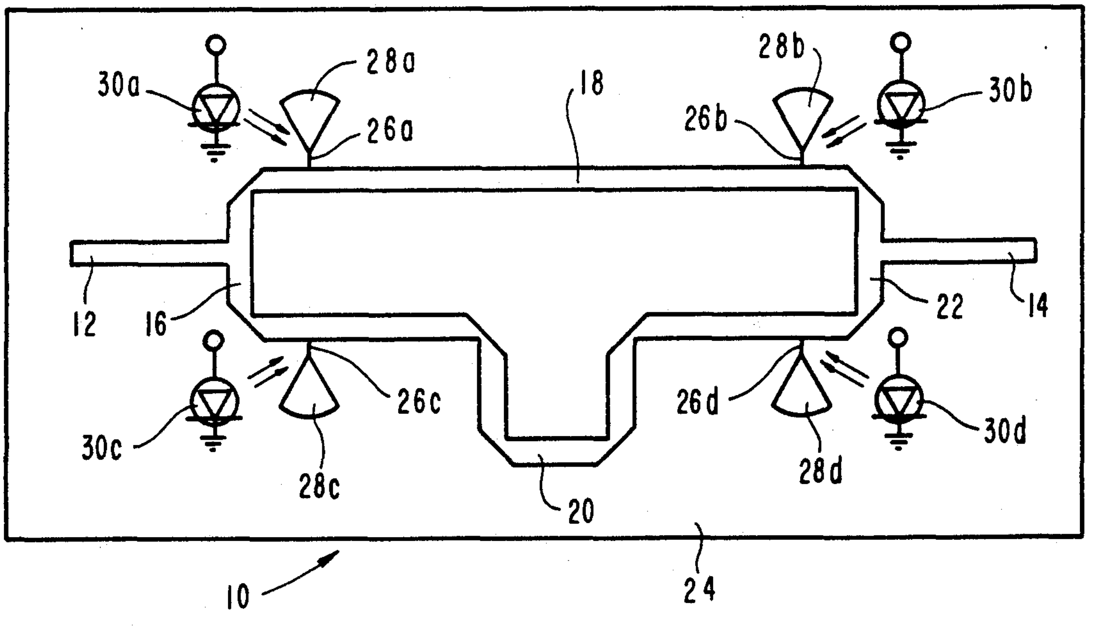
[57] **ABSTRACT**

A phase shifter having a reference path and a delay path, light sources, and superconductive switches. Each of the superconductive switches is terminated in a virtual short circuit, which may be a radial stub. Switching between the reference path and delayed path is accomplished by illuminating the superconductive switches connected to the desired path, while not illuminating the superconductive switches connected to the other path.

9 Claims, 2 Drawing Sheets



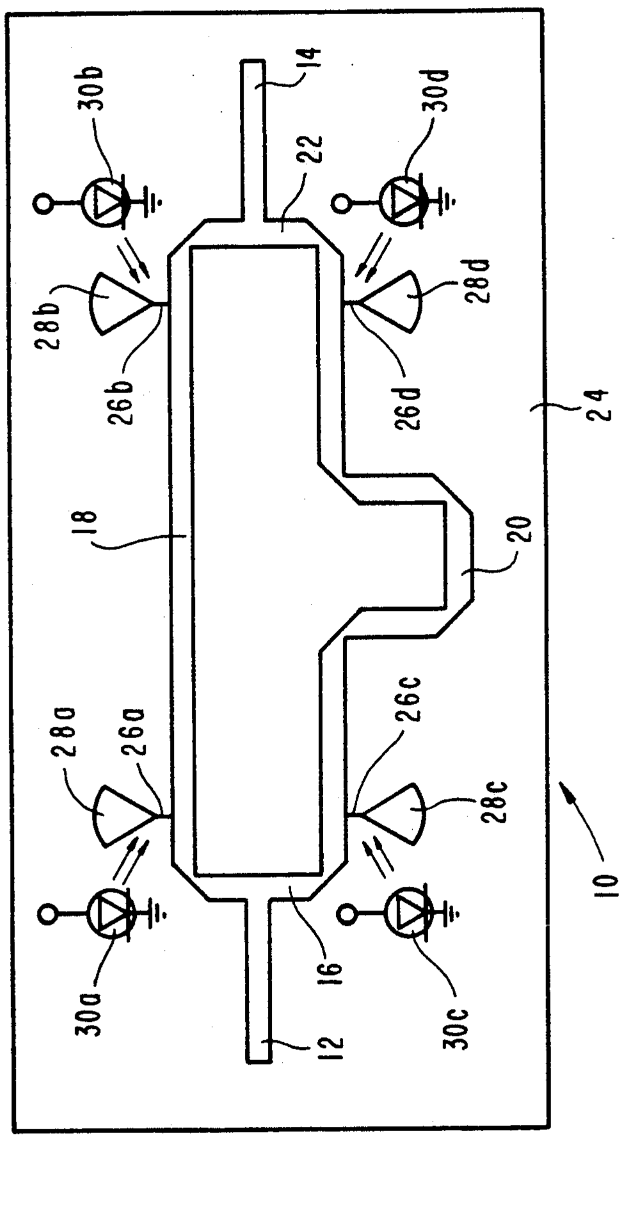

30b
14
30d
22
28b
28d
26b
26d
24
18
20
20
28a
26a
26c
28c
10
30a
16
12
30c

FIG. 1

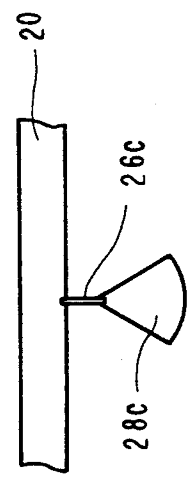
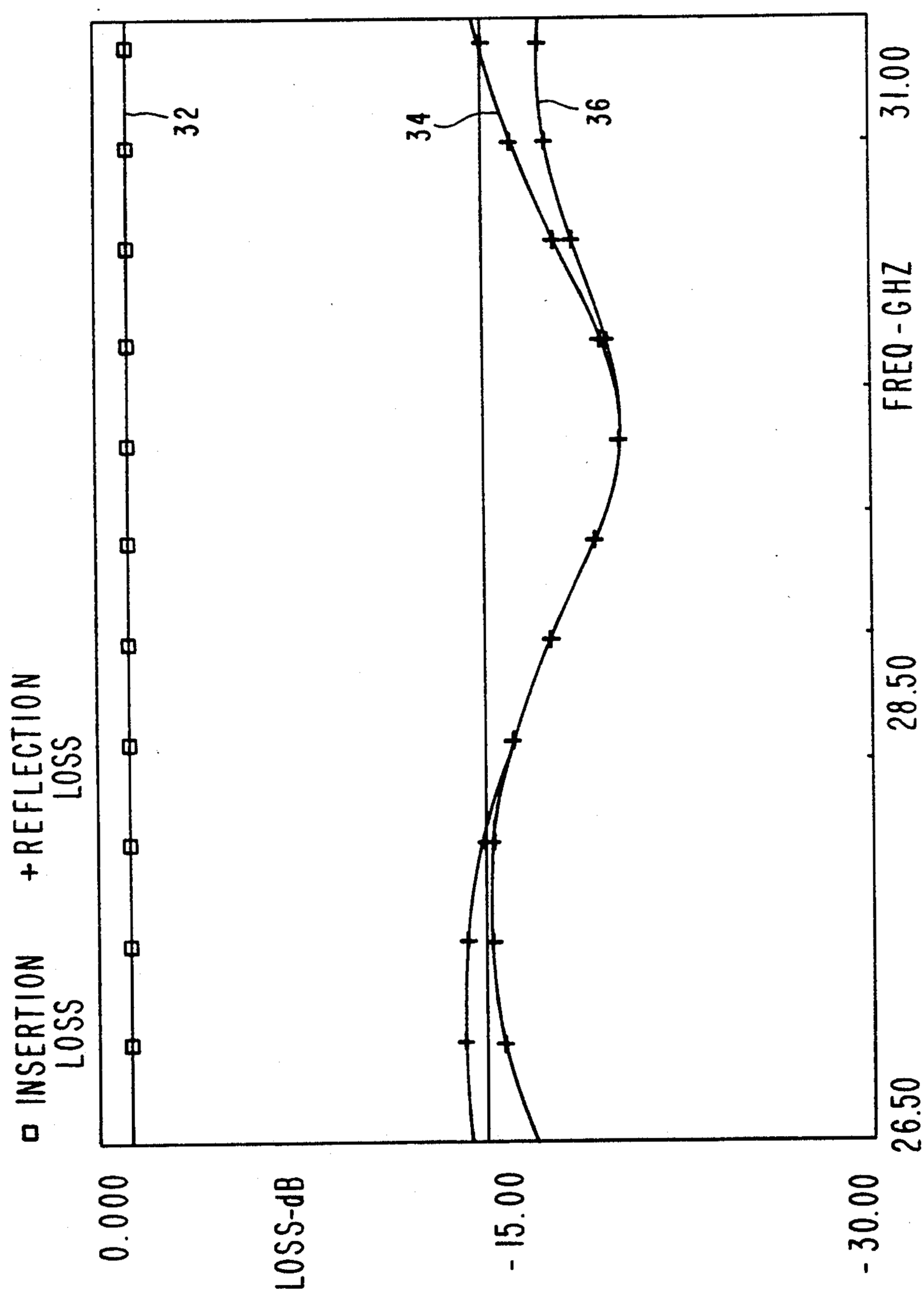

20
26c
28c

FIG. 2

FIG. 3



□ INSERTION LOSS
+ REFLECTION LOSS
0.000
LOSS-dB
-15.00
-30.00
26.50
28.50
31.00
FREQ-GHZ
32
34
36

MONOLITHIC MM-WAVE PHASE SHIFTER USING OPTICALLY ACTIVATED SUPERCONDUCTING SWITCHES

ORIGIN OF THE INVENTION

The invention described herein was made by employees of the U.S. Government and may be manufactured and used by or for the Government for governmental purposes without the payment of any royalties thereon or therefor.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention relates generally to millimeter-wave phase shifters, and more particularly to monolithic millimeter-wave phase shifters using optically activated superconducting switches.

2. Description of the Related Art

Phased-array antennas are increasingly being used in radar systems, e.g. mm-wave radar systems, and in communications systems, e.g. satellite communication systems. These antennas permit electronic beam steering, obviating the need for mechanical pointing. In order to utilize a phased-array antenna, these system must include a phase shifter, which provides incremental offset phase excitation to each element in the array.

Though many types of phase shifters exist, the most desirable is the true time delay type, which can provide frequency independent steering for large arrays. The most popular true time delay phase shifter utilizes a switched line technique. This technique achieves true time delay by switching an input signal between two alternative routes, i.e., a reference path and a delay path. The delay path has a transmission length that is longer than that of the reference path by a portion of the wavelength of the input signal, and therefore causes the signal transmitted therethrough to exit out-of-phase relative to the signal transmitted through the reference path. Field effect transistor (FET) switches or diode switches have been utilized to switch the signal between the reference path and the delay path. Four of these switches are required per bit.

These conventional phase shifters include the following disadvantages: asymmetric insertion loss between the delay path and the reference path, high overall insertion loss, poor isolation between the radio frequency signal and switch bias signals, and signal distribution complexity. The difference in insertion loss between the delay path and the reference path results primarily from variation in the shunt capacitance of the switches during their on and off states. Some investigators have attempted to resonate out the shunt capacitance of the switches during their off state using parallel inductors. This approach has met with only limited success and is difficult to achieve at millimeter wavelengths. The lack of insertion loss symmetry degrades system performance and requires complex and expensive compensation devices. Generally, asymmetric insertion loss due to the different transmission lengths of the reference path and the delay path is minimal in comparison to that caused by variation in the shunt capacitance of the switches.

The total insertion loss of conventional phase shifters is large and is roughly proportional to the reactance associated with the switches, e.g., typically greater than 2 dB per bit at 30 GHz. Also, interaction between the radio frequency signal and the switch bias signals required to control the switches presents another problem. Standing-wave patterns are set-up on the biasing lines, resulting in unpredictable performance and sensitivity to bondwire lengths.

Also, because some of the systems in which conventional phase shifters are used may include hundreds of elements per array and perhaps five bits per element, and because each bit requires a minimum of two control lines to toggle the switches, signal distribution is complex.

SUMMARY OF THE INVENTION

It is an object of the present invention to provide an improved phase shifter that has low overall insertion loss and symmetric insertion loss between the reference path and the delay path.

Another object of the present invention is to provide an improved phase shifter that eliminates interactions between the radio frequency signal and the biasing networks of conventional phase shifters.

Still another object of the present invention is to provide an improved phase shifter having greatly reduced signal distribution complexity, reduced control logic problems and reduced system weight.

In order to achieve the foregoing and other objects, in accordance with the purposes of the present invention as described herein, a phase shifter having an input line with a bifurcation junction and an output line with a rejoining junction, comprises: a reference path and a delay path, each extending from the bifrication junction to the rejoining junction; illumination means for providing light; and switching means operatively connected to the reference path and delay paths for switching between the reference path and the delay path in response to the illumination means.

In the preferred embodiment of the present invention, the switching means includes four switches that are made from a superconductive material. These switches are each terminated in a virtual short circuit. Two of the switches are connected to the reference path, and the other two switches are connected to the delay path. Two of the switches are located about one quarter of a wavelength from the bifurcation junction, and the other two switches are located about one quarter of a wavelength from the rejoining junction. Each of the switches is normally held near its transition temperature, i.e., the temperature at which the switch enters a superconductive state from a resistive state, so that each switch is normally in a superconductive state. The switches on either the reference path or the delay path are selectively illuminated by the illumination means, and thereby enter a resistive state. Alternative embodiments suitable for causing a resistive state include but are not limited to: local application of a magnetic field above the critical field of the superconductor and application of a current through the switch above the critical current of the superconductor. The radio frequency signal entering through the input line is transmitted through the path which has its respective switches in the resistive state and reflected from the other path which has its respective switches in the superconductive state.

These and other features and advantages of the present invention will become more apparent with reference to the following detailed description and drawings.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings illustrate several aspects of the present invention, and together with the description serve to explain the principles of the present invention. In the drawings:

FIG. **1** is a top view of a phase shifter according to the present invention;

FIG. **2** is an enlarged top view of a portion of the phase shifter shown in FIG. **1**; and

FIG. **3** is a graph that shows modeled predictions of loss values at various frequencies for a phase shifter according to the present invention.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

FIG. **1** shows a top view of a phase shifter **10** according to the present invention. Phase shifter **10** includes an input line **12** and an output line **14**. Input line **12** has a bifurcation junction **16**, from which a reference path **18** and a delay path **20** extend. Reference path **18** and delay path **20** meet with output line **14** at a rejoining junction **22**. Input line **12**, output line **14**, reference path **18** and delay path **20** may be, for example, thin-film strips formed on a substrate **24** and are made from a conductive material, such as silver, or a superconductive material, such as Yttrium-Barium-Copper-Oxide (YBaCuO). Phase shifter **10** may be a microstrip circuit, i.e., wherein input line **12**, output line **14**, reference path **18** and delay path **20** are thin-film conductive strips formed on substrate **24**, which is a dielectric material having a thin-film ground-plane conductor (not shown).

Delay path **20** has a greater length than reference path **18**. More specifically, delay path **20** is longer than reference path **18** by a fraction or a multiple of a fraction of the wavelength of a signal entering through input line **12**. Therefore, when the signal enters through input line **12** and travels along and exits delay path **20**, it will be out-of-phase relative to a signal traveling along and exiting through reference path **18**. For example, if the length difference between delay path **20** and reference path **18** is an odd-multiple of half-wavelengths of the signal, then the signal exiting delay path **20** will be 180° out-of-phase relative to the signal exiting reference path **18**.

Phase shifter **10** also includes superconducting switches ***26a*, *26b*, *26c*, *26d***, which may be fabricated from a high-temperature superconductor, e.g., Yttrium-Barium-Copper-Oxide (YBaCuO). Two superconducting switches ***26a*, *26b*** are electrically connected to reference path **18**, and two additional superconductor switches ***26c*, *26d***, are electrically connected to delay path **20**. Each switch ***26a*, *26b*, *26c*, *26d*** is located about one quarter of a wavelength from either bifurcation junction **16** or rejoining junction **22**. That is, two superconducting switches ***26a*, *26c*** are located one quarter of a wavelength from either bifurcation junction **16**, while the other two superconducting switches ***26b*, *26d*** are located one quarter of a wavelength from rejoining junction **22**.

Each of the respective superconducting switch ***26a*, *26b*, *26c*, *26d*** is terminated in a virtual short circuit using radial stubs ***28a*, *28b*, *28c*, *28d***. Radial stubs ***28a*, *28b*, *28c*, *28d***, however, could alternatively be any other type of resonator having high impedance, e.g., rectangular stubs or gap coupled radial stubs. Radial stubs are preferred because they have broader bandwidths. Gap coupled radial stubs may be coupled to superconducting switches ***26a*, *26b*, *26c*, *26d*** through a gap discontinuity having a length that is much less than a wavelength. Gap coupled radial stubs add additional bandwidth due to the transformer-like qualities of the gap discontinuity and may be used as tuning elements to tailor the characteristics of phase shifter **10**. Radial stubs ***28a*, *28b*, *28c*, *28d*** may be formed on a substrate **24** and may be made of any good conductor, such as silver, or a superconductive material, such as YBaCuO. As best shown in FIG. **2**, each of the superconducting switches ***26a*, *26b*, *26c*, *26d*** contacts a respective one of the radial stubs ***28a*, *28b*, *28c*, *28d*** and either reference path **18** or delay path **20**.

Phase shifter **10** also includes light sources ***30a*, *30b*, *30c*, *30d*** each respectfully associated with one of the superconducting switches ***26a*, *26b*, *26c*, *26d***. Light sources ***30a*, *30b*, *30c*, *30d*** may be formed on substrate **24** and may be LEDs as shown in FIG. **1**. Alternatively, light sources ***30a*, *30b*, *30c*, *30d*** may be, for example, lasers, laser diodes, and/or optic fibers.

Phase shifter **10** may be monolithic, i.e., wherein input line **12**, output line **14**, reference path **18**, delay path **20**, superconducting switches ***26a*, *26b*, *26c*, *26d***, radial stubs ***28a*, *28b*, *28c*, *28d***, and light sources ***30a*, *30b*, *30c*, *30d*** are formed in or on substrate **24**.

Superconducting switches ***26a*, *26b*, *26c*, *26d*** operate in the bolometric mode, i.e., superconducting switches ***26a*, *26b*, *26c*, *26d*** are normally held in a temperature region near their transition temperature, so that the superconductive switches ***26a*, *26b*, *26c*, *26d*** are normally in a superconductive state or a nearly superconductive state. In this temperature region, e.g., approximately 80° K. for YBaCuO, the temperature derivative of resistance (dR/dT) is maximum. Light emitted from light sources ***30a*, *30b*, *30c*, *30d*** raises the temperature of superconducting switches ***26a*, *26b*, *26c*, *26d*** and consequently causes superconducting switches ***26a*, *26b*, *26c*, *26d*** to enter a resistive state. Alternatively, light sources with energy greater than the superconductor band gap can be used to dissociate the superconducting electron pairs and cause the transition from a superconducting to a resistive state.

A signal entering input line **12** is directed to either reference path **18** or delay path **20** depending on the state of superconducting switches ***26a*, *26b*, *26c*, *26d***. Reference path **18** and delay path **20** do not operate in a power splitting mode, and therefor each maintains the same characteristic impedance, for example, a fifty ohm characteristic. For example, if superconducting switches ***26a*, *26b*** associated with light sources ***30a*, *30b*** are illuminated, these superconducting switches ***26a*, *26b*** will enter a resistive state. In addition, superconducting switches ***26c*, *26d*** associated with the delay path **20** are not illuminated by their respective light sources ***30c*, *30d*** and are consequently in a superconductive state. Because superconducting switches ***26c*, *26d*** associated with delay path **20** are respectively positioned one quarter of a wavelength from the bifurcation junction **16** and the rejoining junction **22**, the signal is reflected in-phase from delay path **20** to bifurcation junction **16** and rejoining junction **22**. Therefore, when superconducting switches ***26a*, *26b*** associated with reference path **18** are illuminated by their corresponding light sources ***30a*, *30b***, and superconducting switches ***26c*, *26d*** associated with in delay path **20** are not illuminated by their corresponding light sources ***30c*, *30d***, the signal entering input line **12** will be transmitted only through reference path **18**.

On the other hand, to achieve the desired phase shift, superconducting switches **26c, 26d** associated with delay path **20** are illuminated by their corresponding light sources **30c, 30d** while superconducting switches **26a, 26b** associated with reference path **18** are not illuminated by their corresponding light sources **30a, 30b.**

Preferably, superconducting switches **26a, 26b, 26c, 26d** have an aspect ratio, i.e., the ratio of length over width, of about 25:1. For example, superconducting switches **26a, 26b, 26c, 26d** may be about 0.005 inches long and about 0.0002 inches wide. The resistivity of superconducting switches **26a, 26b, 26c, 26d** while illuminated by light sources **30a, 30b, 30c, 30d** depends upon the thickness and the resistivity of the material from which they are made. For example, superconducting switches **26a, 26b, 26c, 26d** having a thickness of about one micron produce a resistance of about 250 ohms to about 500 ohms when illuminated by light sources **30, 30b, 30c, 30d.** The efficiency of superconducting switches **26a, 26b, 26c, 26d** is inversely proportional to the product of their resistance in the superconducting state and their resistance in the resistive state. Theoretically, this efficiency would tend toward infinity if the surface resistance was vanishingly small. However, the superconductive state of the superconducting switches **26a, 26b, 26c, 26d** need not be perfectly superconducting to guarantee a high degree of insertion loss symmetry.

FIG. **3** shows modeled predictions of insertion loss for a 180° phase shifter according to the present invention within a selected frequency range. This data required that the surface resistance of the superconductor be only as good as normal metal at 77° K. when in the superconducting state. Superconducting switches **26a, 26b, 26c, 26d** were treated as distributed resistors to insure modeling accuracy. Linear curve **32** is a plot of insertion loss for both reference path **18** and delay path **20.** Thus insertion loss between reference path **18** and delay path **20** is exceptionally symmetric. Also, overall insertion loss is low, i.e., less than 2 dB. In addition, a curve **34** shows reflection loss for reference path **18** and a curve **36** shows reflection loss for delayed path **20.** Though not quite symmetric, return loss is excellent, and is generally less than 15 dB through a major portion of the modeled frequency range. Phase shifters according to the present invention overcome the symmetry limitations of conventional phase shifters. Therefore, system performance is enhanced in comparison to conventional phase shifters, and the need for complex compensation devices is negated. Also, phase shifters according to the present invention reduce total insertion loss, thereby increasing system efficiency.

Another advantage of phase shifters according to the present invention is signal isolation. More precisely, a phase shifter of the present invention eliminates interactions between radio frequency signals and the switch bias lines of conventional phase shifters. In the present invention there are no bias lines on which standing-wave patterns can be set up as in conventional phase shifters.

In addition, phase shifters according to the present invention inherently reduce signal distribution complexity, as well as overall system weight.

Numerous modifications and adaptations of the present invention will be apparent to those so skilled in the art. For example, light sources **30, 30b, 30c, 30d** may include optic fibers to further reduce signal distribution complexity and overall system weight. In addition, a phase shifter according to the present invention may include more than one delay path. Also, radial stubs **28a, 28b, 28c, 28d** may instead be rectangular stubs or gap coupled radial stubs. Thus, it is intended by the following claims to cover all modifications and the adaptations which fall within the true spirit and scope of the invention.

What is claimed is:

1. A monolithic phase shifter having an input and an output, comprising:

a substrate;

a bifurcation junction operatively connected to the input and forming a reference path and a delay path;

a rejoining junction operatively connected to the output and joining said reference and delay paths;

first and second light-activated, superconducting switches disposed in said reference and delay paths, respectively, each switch being about one quarter wavelength from the bifurcation junction;

third and fourth light-activated, superconducting switches disposed in said reference and delay paths, respectively, each switch being about one quarter wavelength away from the rejoining junction;

first illumination means for providing light to said first and third switches;

second illumination means for providing light to said second and fourth switches, said first and second illumination means providing light alternately, and

wherein said bifurcation and rejoining junctions, said reference and delay paths, and said switches are formed on said substrate.

2. A phase shifter as recited in claim **15,** further comprising:

stub means operatively connected to said superconducting switches for terminating said superconducting switches in a virtual short circuit.

3. A phase shifter as recited in claim **2,** wherein:

said stub means includes a radial stub.

4. A phase shifter as recited in claim **1,** wherein:

said superconductive material is Yttrium-Barium-Copper-Oxide.

5. A phase shifter as recited in claim **4,** wherein:

said reference and delay paths include silver.

6. A phase shifter as recited in claim **1,** wherein:

said illumination means includes at least one light emitting diode.

7. A phase shifter as recited in claim **1,** wherein:

said superconducting switches each have an aspect ratio of about 25:1.

8. A phase shifter as recited in claim **7,** wherein:

said superconducting switches each have a width of about 0.0002 inches and a length of about 0.005 inches.

9. A phase shifter as recited in claim **8,** wherein:

said superconducting switches each have a thickness of about one micron.

* * * * *